

AN INDEX FOR SOIL PORE SIZE DISTRIBUTION

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ABSTRACT

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An index for classifying soil pore size distribution is proposed. The arithmetic mean change in percent soil water content by weight as the tension changes from zero to 1.5 bars is used as the index. This number characterizes the size distribution of pores with a radius of one micron or greater. A simple equation is presented to calculate the index from soil water contents at pressure plate settings of zero, 0.2, and 1.5 bars. Moisture release curves from 3 different soils show that the index does tend to characterize the shape of the release curve and that it is sensitive to past management which affects the distribution of large soil pores. When all other conditions are optimum, it appears that there exists a specific value of the index which indicates when the soil pore size distribution may be expected to limit plant growth. It is further suggested that the index, together with penetrometer measurements made at the 1.5-bar water content, may be used as "soil test values" for making practical management decisions and for predicting the stability of soils under varying field conditions.

INTRODUCTION

Of all the physical measurements which have been used to characterize various aspects of soil structure, the pore-size distribution is one of the most pertinent, so far as plant growth is concerned. A number of scientists have reported studies of pore size distribution as it affects plant growth and as a general method for defining the structure of porous materials (Barden and Pavlakis, 1971; Croney and Coleman, 1954; Dullien and Batra, 1970; and Sridharan et al., 1971).

A complete analysis of the pore size distribution of a soil is useful for predicting water infiltration rates, water availability to plants, water-storage capacity, and aeration status. However, for many practical soil management decisions, detailed pore size distribution may not be needed. A single number characterizing the important aspects of the distribution would suffice and even be preferable for people not specifically trained in soil physics (Bolt et al., 1959).

Two requirements stand out as one considers soil porosity with specific reference to plant growth.

(1) The soil must have enough large pores to allow rapid infiltration of surface water

followed by early drainage so that oxygen does not become limiting. Large pores also favor the initiation of root growth.

(2) The soil should have an extensive group of pores small enough to resist gravitational drainage, yet large enough to release significant quantities of water to plant roots without forcing the water in the roots to fall to low energy levels.

Approximate values may be assigned to these two criteria. For example, some of the pores must be greater than $200\ \mu$ in diameter to encourage root elongation (Williams and Cooke, 1961). Their size distribution must also be such that saturated conditions do not occur for more than a few minutes following surface wetting so that the soil returns within a few hours to an air-filled void state of 10% for most plants (Baver and Farnsworth, 1940) and to as much as 15% for oxygen-sensitive plants such as potatoes (Bushnell, 1953; Eavis, 1972).

The smaller pore-size group, which restrains water from deep drainage yet readily releases it to plant roots, is responsible for the amount of "available water" in the soil. Ideally, this quantity of water should be as large as possible without sacrificing adequate infiltration and aeration. Moreover, water held in the "available" range should be released at low suctions to promote rapid plant growth. As pointed out by Slatyer (1967, p.299), "even small internal water deficits can be expected to reduce plant growth". Maximum water release above -1 bar soil matric potential is desirable (Hsieh et al., 1972), even though plants may grow reasonably well in deep, heavy textured soils with water at several bars negative potential.

THEORY

The soil-water desorption curve interpreted through the concept of capillary rise is a logical way to proceed with analysis of pore size distribution. When one considers the hypothetical desorption curve shown in Fig.1, it is obvious that its shape reflects the state

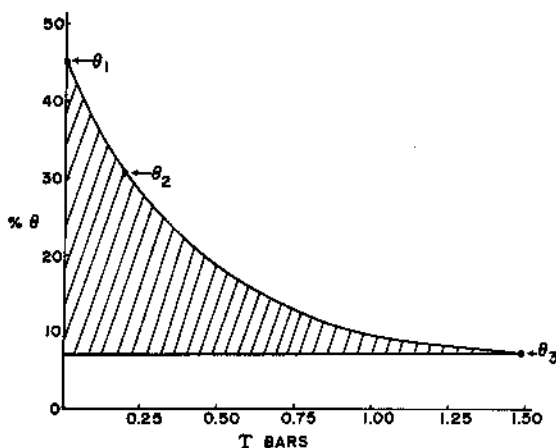


Fig.1. A hypothetical soil-moisture desorption curve showing the shaded area represented by A in eq.4.

of several important soil physical properties. If the soil represented by this curve were compressed to increase its bulk density and reduce the size of its larger pores, its water-release curve would be flattened. Compaction until all pores greater than 1μ in radius were filled with solids would result in a straight release curve between zero and 1.5 bars, as shown by the line at the bottom of the shaded area. As far as plant growth is concerned, let us say that this horizontal line passing through the 1.5-bar water content represents a "zero" state for any given soil. Any increase, then, in the area between the zero state or base line and the real moisture-release curve of the soil indicates an improvement.

Tabuchi (1971) has derived an equation to describe soil water release curves that resulted in:

$$W = C_1 \exp C_2 \tau + C_3 \quad (1)$$

where W is water content, C_1 , C_2 , and C_3 are constants for any one soil, and τ is the tension. Our experience indicates that the agreement between the equation and real soils in the range of zero to 1.5 bars suction can be improved by using an additional empirical term representing a straight line passing through θ_3 at $\tau = 1.5$ with a slope ℓ of -1 , giving:

$$\theta = a \exp(-b\tau) + (\theta_3 + 1.5 + \ell\tau) \quad (2)$$

where θ is the percent water content on a dry weight basis and τ is the matrix suction in bars (a positive number). The constants a and b are evaluated at $\tau = 0$ and $\tau = 0.2$, giving $a = \theta_1 - \theta_3 - 1.5$, $b = 11.5 \log_{10} [a/(\theta_2 - \theta_3 - 1.3)]$ where θ_1 , θ_2 , and θ_3 are the water percentages in equilibrium with pressure plate settings of 0, 0.2, and 1.5 bars, respectively.

The area represented by the shaded portion in Fig. 1 is given, then, as:

$$A = \int_0^{1.5} [a \exp(-b\tau) + \theta_3 + 1.5 - \tau] d\tau - 1.5[a \exp(-1.5b) + \theta_3] \quad (3)$$

or:

$$A = a/b + 1.13 - (1.5 + 1/b) a \exp(-1.5b) \quad (4)$$

so that:

$$A \approx a/b + 1.13 \text{ when } b > 3 \quad (5)$$

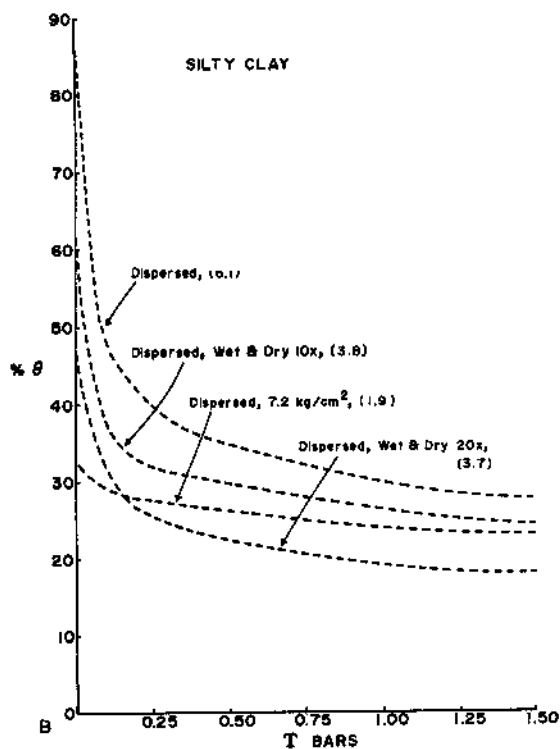
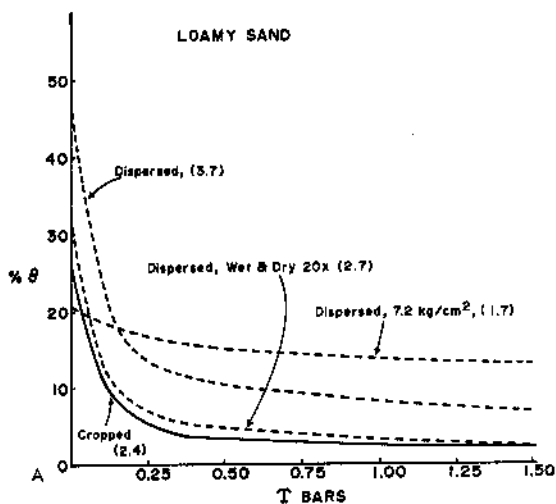
which only requires the measurement of water percentages θ_1 , θ_2 , and θ_3 to evaluate A .

It is convenient, then, to define the porosity index as

$$I = A/1.5 \text{ bars} \quad (6)$$

so that I is dimensionless and carries the physical concept of the arithmetic mean change in water content as the tension increases from zero to 1.5 bars.

Eq. 2 describes a curve which, of course, passes exactly through the measured values of θ_1 and θ_2 . For all the cases presented in Fig. 2 of this paper, the curves also pass very near the measured values of θ_3 , the greatest deviation being 0.1 of a percent water content.



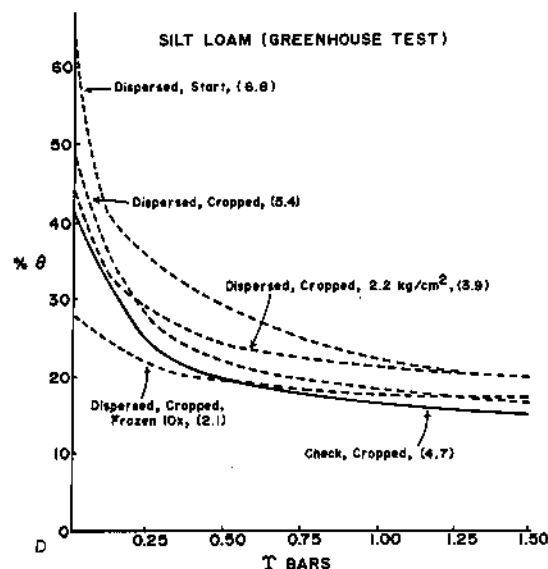
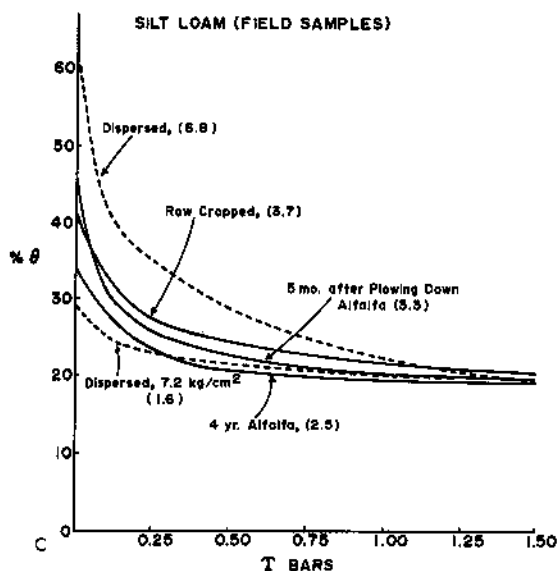


Fig. 2. Moisture desorption curves for soils with three different textures. The curve parameters indicate the soils' recent history in terms of mechanical dispersion, loading when wet, number of wetting and drying or freezing and thawing cycles, and type of past cropping in the case of undisturbed cores. The porosity index for each curve is given in parentheses.

Water contents for each curve were also determined at pressures of 0.1, 0.3, 0.5, and 1.0 bars, and they fall within 1% water content of the values predicted by eq. 2.

Although eq. 2 and 4 assume a soil-air entry value approaching zero, actual values of 10 or 20 cm of water will not cause a significant error in the value of I compared to the

effects of errors encountered in sampling and water content determinations. If, however, the air-entry values should rise as high as 100 cm of water, eq.2 will generally not describe the water release curve with acceptable accuracy. If a heavy clay soil is being used, the air-entry value should be checked before applying eq.5.

Soil-water contents must be carefully determined. Experimental errors or variations greater than 1% water content at the 0.2- and 1.5-bar tensions will cause significant changes in the value of I . It is best to determine the 0-, 0.2-, and 1.5-bar water contents all on the same sample, but include several samples from the same area or treatment. Changes of I less than 0.2 will not be meaningful, for natural variation may often be greater.

With the exception, then, of soils having uncommonly large air-entry values, I may be used to characterize the soil-moisture curve and, more directly, as an index for the state of soil porosity in the range of 0 to 1.5 bars. Though the index is specifically for the state of the soil at the time of measurement, it may also be used to predict the stability of the soil under field conditions by simulating field variables on samples in the laboratory before measuring I .

DISCUSSION OF SOME EXAMPLES

Fig.2A shows the effects of several treatments on the moisture-release curve of a loamy sand. The number in parentheses following the description of each curve is the porosity index, I , defined by eq.6. Undisturbed samples were taken from a row-cropped field and used to find the curve shown by the solid line. Duplicate samples were mechanically dispersed with a high-speed mixer in a distilled water suspension, dried, and then sieved. Some samples were then wet and dried at 60°C twenty times, whereas others were nearly saturated and compressed with a static load of 7.2 kg/cm² before measuring their release curves. Each curve is the average of at least three supposedly identical samples.

The results from similar treatments on a silty clay are shown in Fig.2B. Again alternate wetting and drying decreased the number of larger pores, whereas loading at water contents near saturation was even more detrimental.

Moisture release curves for undisturbed samples taken from 3 different field plots are shown in Fig.2C. It is apparent that they fall more or less in an envelope formed by the 2 curves for the same soil mechanically dispersed and then compacted in the laboratory. The relatively low porosity index for the soil samples taken from the field which had been in alfalfa for 4 years is of particular interest.

The silt loam used to prepare the dispersed samples shown in Fig.2C was also used in Fig.2D. In this case, the solid line showing the check was from the bulk field sample passed through a 2-mm sieve after air-drying in the laboratory. Subsamples from the bulk sample, as well as its dispersed counterpart, were placed in lucite columns and cropped in the greenhouse for approximately 6 months. Tomatoes were grown first, followed by wheat. After the cropping period, the center portions of the columns were sliced into 2-cm thick sections, and some were treated by loading under 2.2 kg/cm², or by freezing and thawing at temperatures of -5° and 25°C ten times. The sharp decrease in large pores

caused by the 10 cycles of freezing and thawing is particularly interesting. This type of action has also been noted by Benoit and Bornstein (1970). Of course, there can be many different intensities of freezing and thawing, as well as wetting and drying, which may interact and lead to other than the detrimental effects noted here.

Fig.2 shows that the moisture release curve is a responsive function of soil management (see also Croney and Coleman, 1954; Sridharan et al., 1971; Warkentin, 1971; Bruce, 1972; Taylor, 1972). The proposed porosity index does tend to characterize this function in terms of a single number. An additional point should also be noted. The moisture tensions to which these soils readily drain are approximately 0.1, 0.3, and 0.35 bar for the loamy sand, the silt loam, and the silty clay, respectively. As already pointed out, enough rapid drainage to provide 10 to 15% air-filled void space is required for satisfactory plant growth. Inspection of Fig.2 suggests this only occurs when these soils have a porosity index in the neighborhood of 2.5 or larger. Moreover, it is obvious that the amount of soil water stored in the optimum tension range (1.5 bars or less) becomes quite small as the index falls below 2.5. It seems reasonable to suppose, then, that there is a value of the pore-size index which may be used to signal the approach of a critical soil physical condition which might be used in the same way soil tests are used for levels of phosphorous and other plant nutrients.

Even though pore-size distribution is one of the most important soil physical quantities which affect plant growth, it is not inclusive. Strength is also important. Penetrometer measurements have been used to correlate soil strength and plant root growth (Taylor, 1971), though some of the available data are confounded by such variables as the method of measurement and the soil water content. Nevertheless, penetrometer measurements might well be utilized with the pore size index proposed here. If a standard method were chosen (Davidson, 1965) and used on each sample after it was brought to the 1.5-bar water content, the results should indicate any approach toward a strength which might limit plant growth under otherwise optimum conditions.

CONCLUSIONS

We feel the proposed soil porosity index, combined with penetrometer measurements made at the 1.5-bar water content, will provide useful information for making practical management decisions on tillage requirements, crop rotation effects, and other farm practices as they relate to the physical condition of the soil in the root zone. Not only does the test characterize the present state of porosity and strength of the soil in the range most important to optimum plant growth, but it may be used to predict stability or to anticipate its change by bringing undisturbed samples into the laboratory and subjecting them to simulated field variables such as wetting and drying, freezing and thawing, and mechanical action.

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